How to Win in High-Volume Manufacturing of Flexible/Printed Electronics

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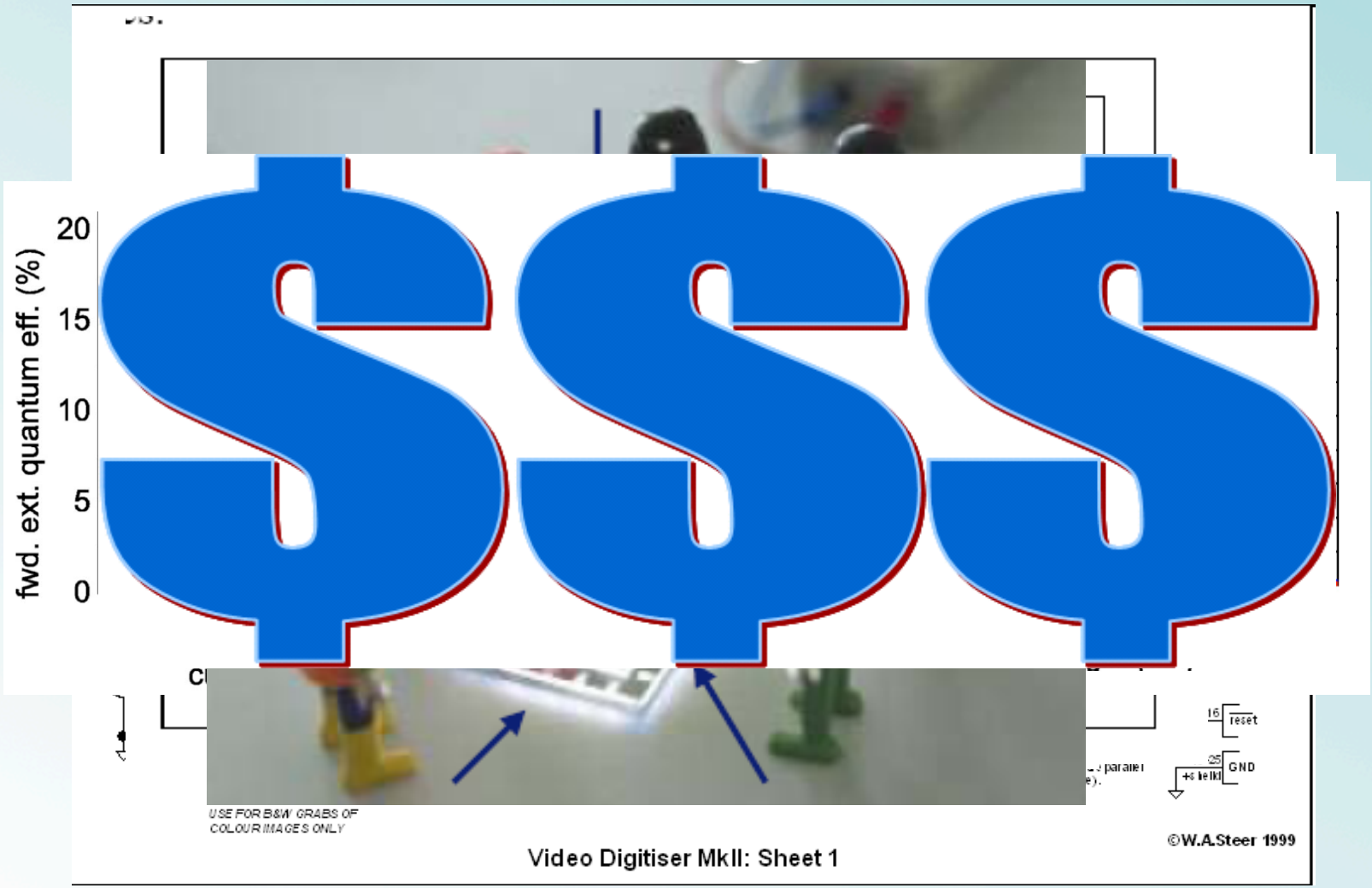
Before Beginning

- Overview of nascent flexible/printed electronics industry and the opportunity space – Why we should be positive
- What to worry about (why other technologies will remain competitive)
- My background:
  - Research:
    - Nitto Denko: Materials for electronics and display applications, including OLED emitters, photorefractive polymers, compensating films, refreshable holographic display
    - Optically active and conducting polymers
  - Beyond the lab:
    - Sloan Fellowship at Stanford Business School, 2004-05
    - Assorted business development and marketing roles in startups in solar energy, biotech and quantitative marketing
    - FlexTech Alliance (Trade Association), Director, Tech. Marketing

Outline

- Brief technical bit
- Define the terminology
- Demand and technology drivers
- Attention-getting markets
- Market predictions and opportunities
  - Drivers
  - A case study on market growth
- Satellite views on technology development

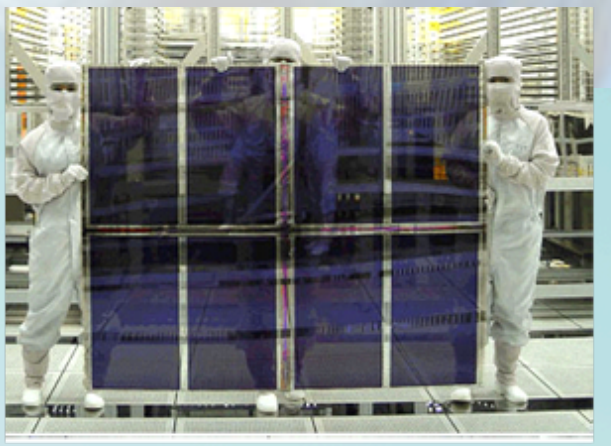
The Technical Portion



New Trends in Electronics

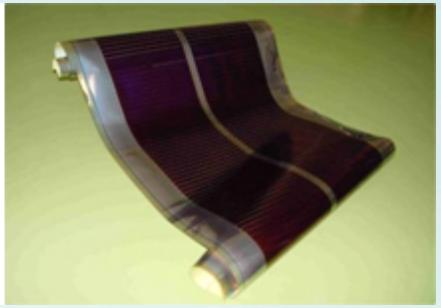
Electronics products are becoming larger – no longer just “micro” or “nano”

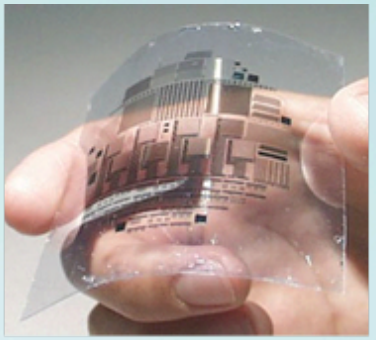
Performance requirements (ruggedness, low-weight, power savings, shape) demand that products be flexible and deformable



Millions of transistors made on glass surface to control display pixels

Flexible solar cells on ultra-thin steel foil (Energy Conversion Devices)





Transistors on plastic transparent substrate (Penn State University)

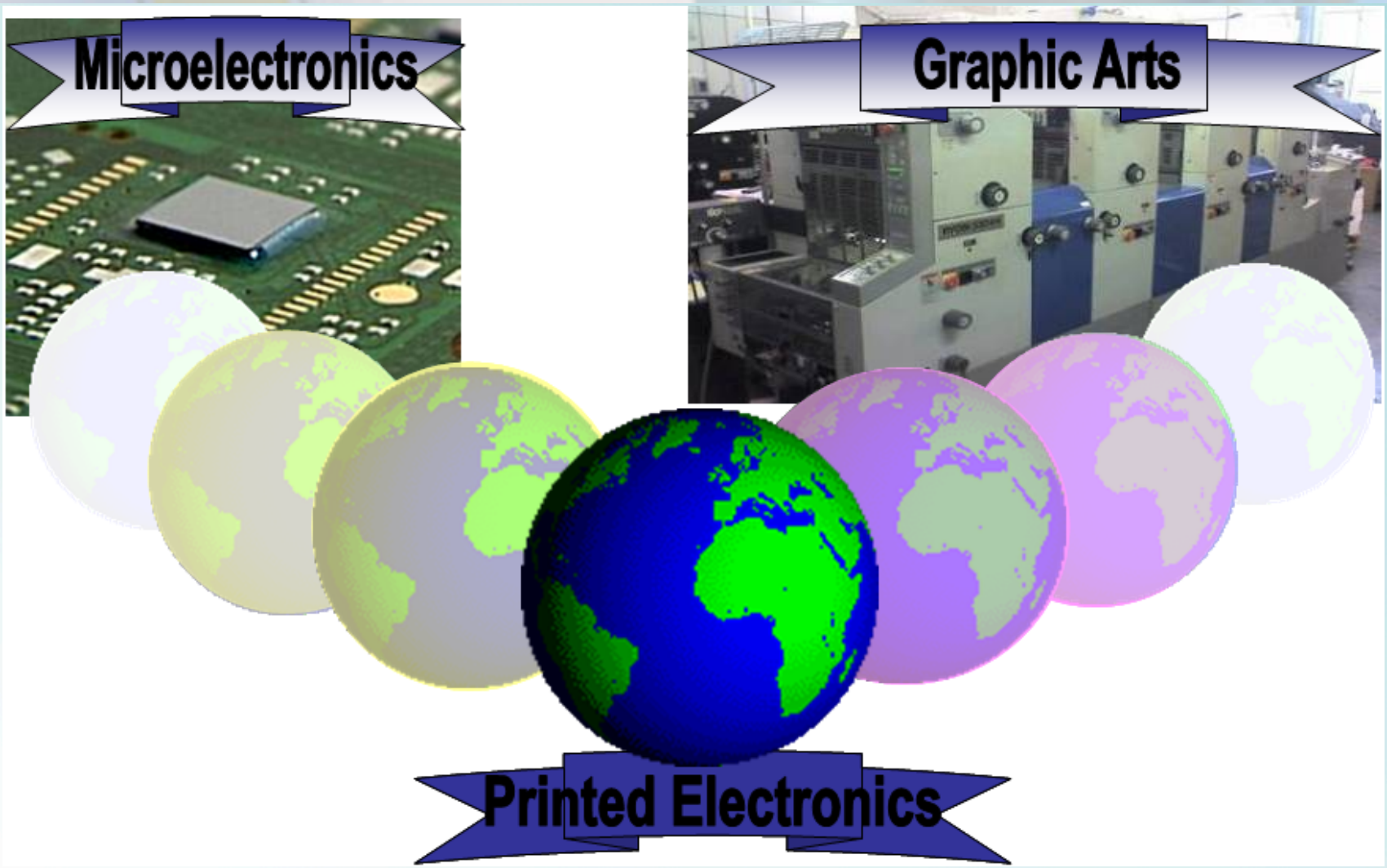
Flexible & Printed Electronics "More or Less than Moore"

- A departure from self-fulfilling focus on transistor density (↑performance, ↓ unit cost)
- Focus on enabling appropriate functionality at low cost

	Flexible & Printed	**Silicon**
Transistors	Thousands	Billions
Feature Sizes	10's of microns	10's of nm
Cost of Fab	$ 5-200 M/fab	$ 2-3 B/fab
Performance	Low	HIgh

The Definition Problem With Flexible and Printed Electronics

Printed Electronics
A Convergence of Two Worlds
(manufacturing innovation – cost reduction)



Flexible Electronics
Enabling Ubiquitous Electronics
(feature innovation – value creation)

Auto Heads-Up and Dash Integrated Display

Magazine with Integrated Display

Portable, Self-powered Command Center

Warring Manufacturing Philosophies

Roll to Roll vs. discrete substrate

- All IC and Display manufacturing today is with discrete substrates
  - Glass substrates are extremely large
  - Batch processes, multiple steps, lots of thermal cycling
- Roll to Roll processing offers continuous flow of process
  - Can be modularized for different unit steps or integrated into complete line

Opportunities in Flexible and Printed Electronics (Overview)


Printed Electronics EUROPE08
Molecular FETs
Displays
NEW! PCBM Library
A Family of Efficient and Diverse n-Type Organic Semiconductors
PCBM
Where economics, engineering meet
Death to Barcodes
PRINTED CIRCUITS SOON WILL BE CHEAP ENOUGH TO TRACK GROCERIES.
Wrapper to track freshness of food
ORGANIC ELECTRONICS
Information Technology & Electroni
Innovative devices, components, or structures--either electric
tailored organic materials and process technologies. In org
structures and materials participate in or are essential to a
that can occur within electrical or optical systems.
Organic Electronics
RFID
Nanocrystals
50nm

Demand Drivers

- Lower Cost
  - Bill of Goods
  - Mfg Complexity
  - Economies of Scale
- New Features/Usability
  - Flexible/Conformable
  - Thickness – new apps
  - Durability
  - Weight
  - Power budget

Flex/Printed Electronics Timeline

1ST GENERATION

Passive Components

- Capacitors, resistors, conductors, inductors
- RFID antenna

2ND GENERATION

Active Printed Components

- TFTCS for ePaper, eBook
- Thin-film Solar Cell
- µ-Battery

TODAY

3RD GENERATION

Completely Printed Active Devices

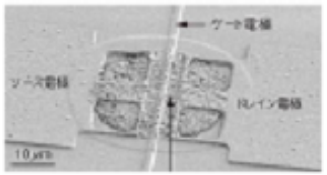
- Color Display w/TFT- PLED
- Complete RFID circuit
- SRAM, CPU

Circuit board with metal ink

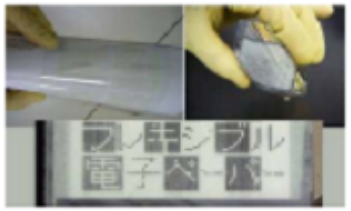
RFID antenna

Passive PE display by Aveso

Flexible Solar Cell by Sharp



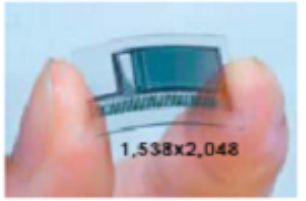
TFT by inkjet / lithography combo *Source: Epson news*



Flexible TFT & e-paper
Source: Toppan news

LTPS-TFT-Q-XGA

RFID R2R



TFT-SRAM (16bits)
Source: Epson news

Source: Nanogram corporation

Flexible/Printable Devices

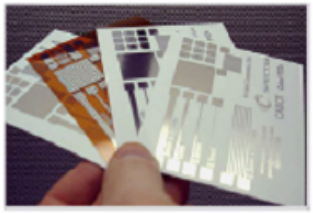
Aveso display

TFE memory

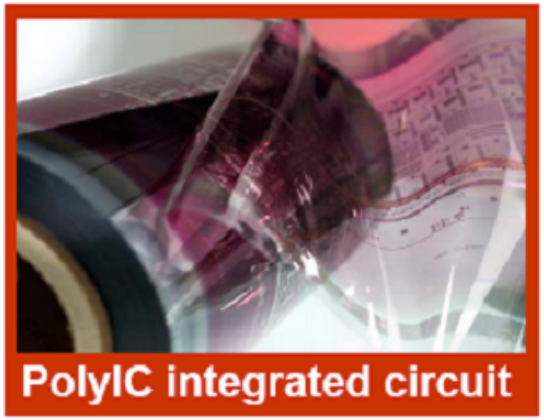
Siemens OLED

Precisia antenna

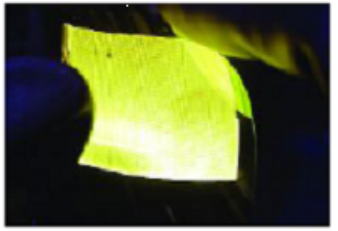
Plastic Logic i-ink



Dimatix circuit board



PolyIC integrated circuit



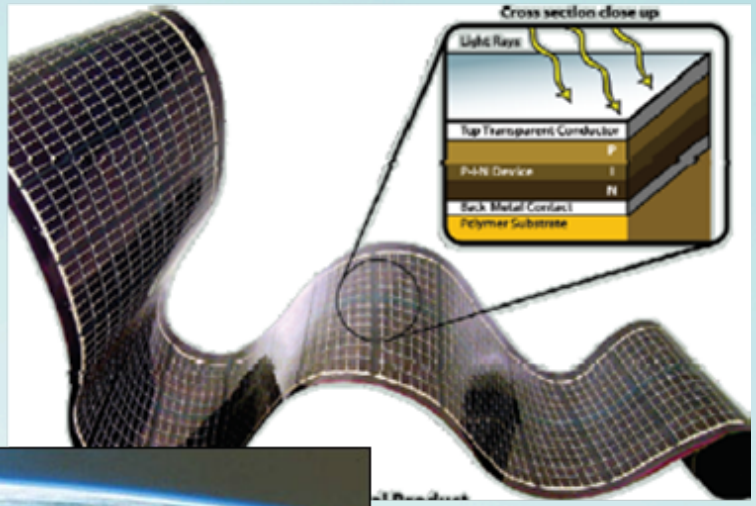
Dupond OLED

Power Paper battery

Konarka solar cell

Photovoltaics

PV Production Growth Rate: 60% y/y (and increasing)
Thin-film PV Growth Rate >100% y/y
Long-term literally hundreds of square kilometers(!) of devices



Flexible/Portable (OLED) Lighting

CROSSLINK™ Portable Lighting

OSRAM-Mauer OLED Lamp

Flexible Digital Displays

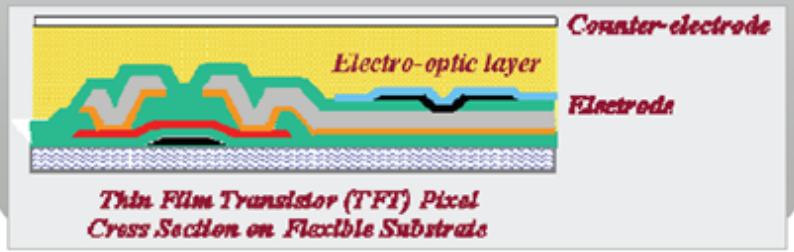
Reflective
Bi-stable "zero power"

E·INK
Electrophoretic Ink

KENT DISPLAYS INCORPORATED
Cholesteric Liquid Crystal

Emissive
Efficient low power

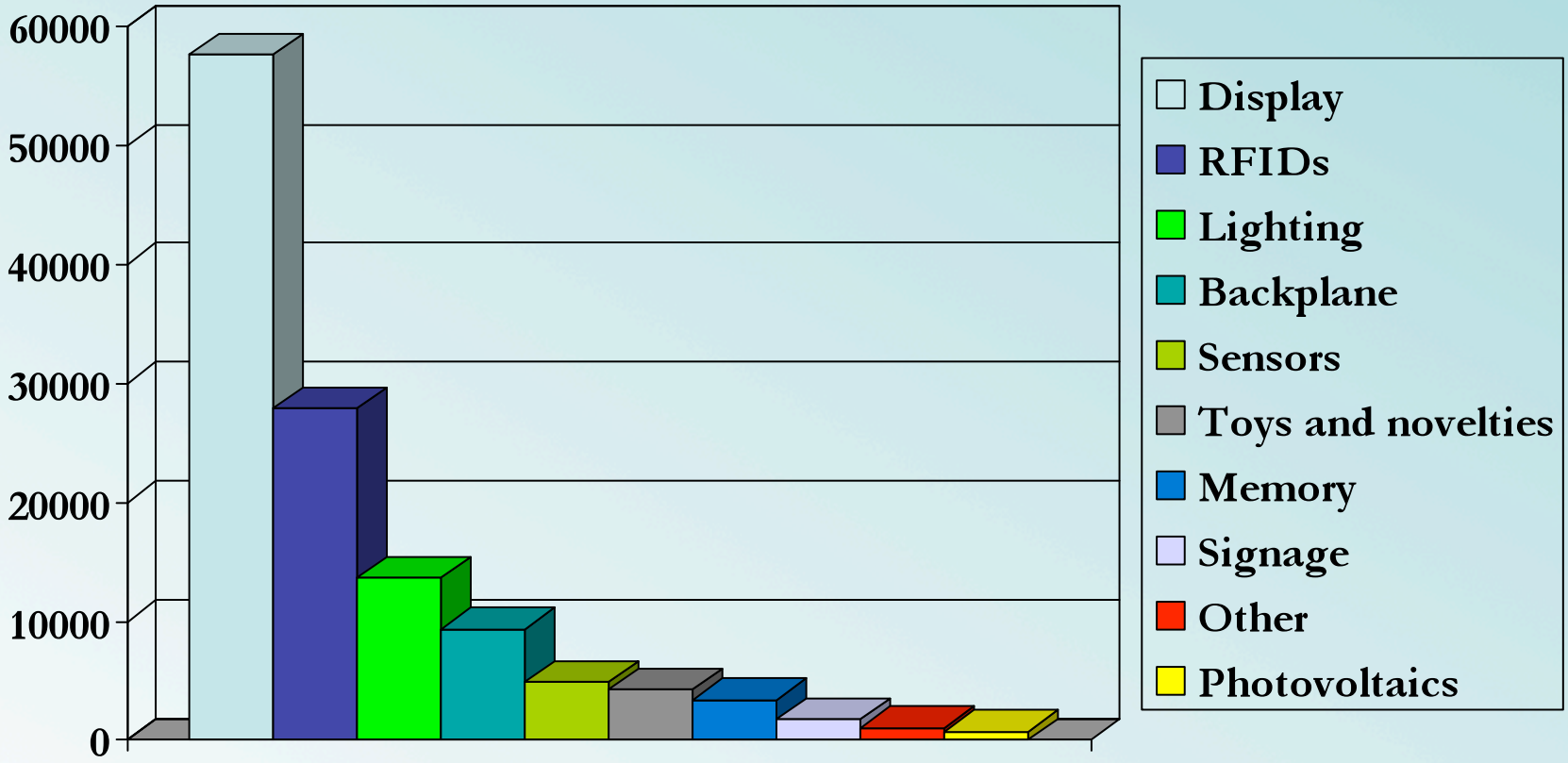
UNIVERSAL DISPLAY CORPORATION™
Phosphorescent OLED



Flexible Displays in Product Packaging/Marketing

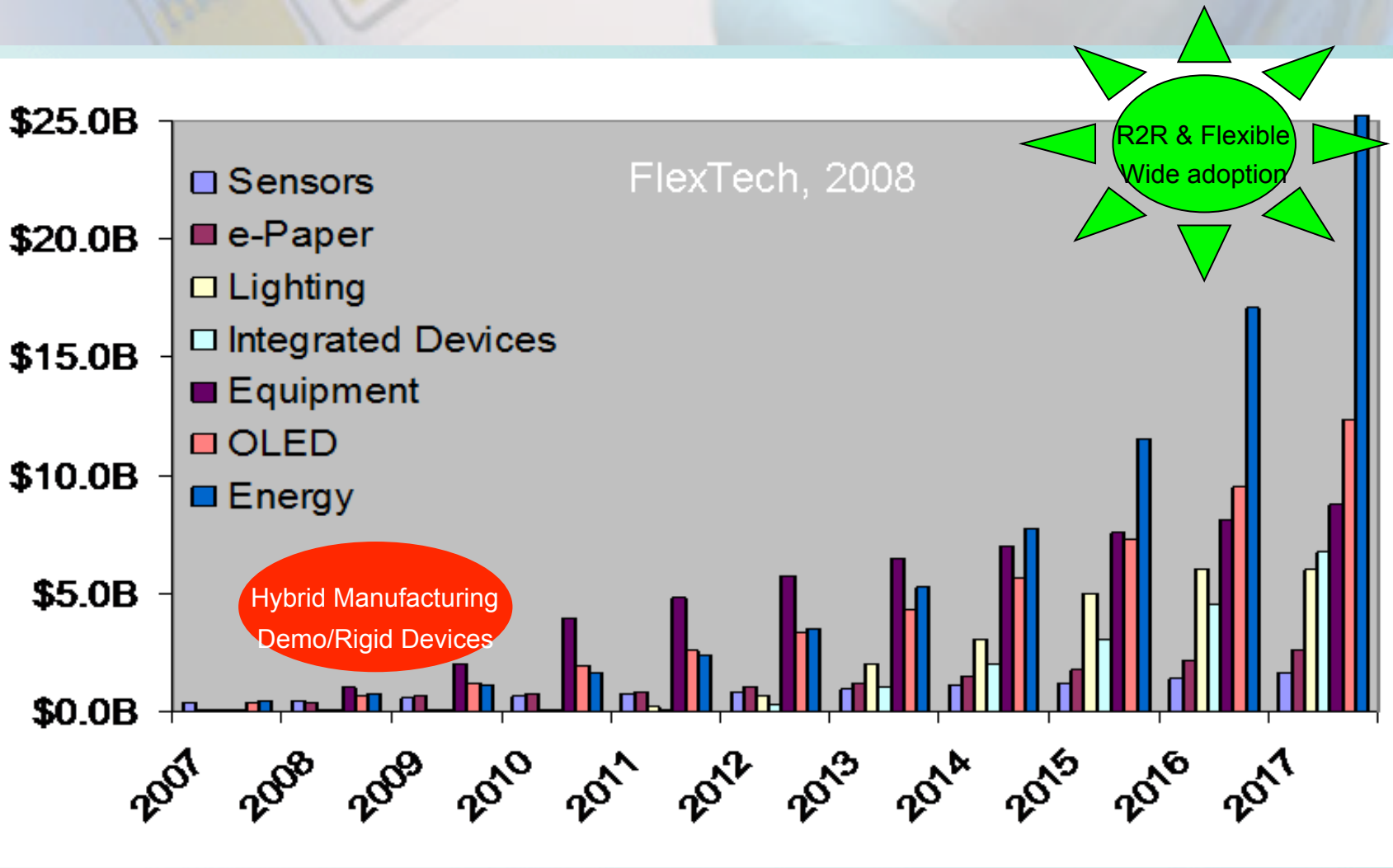
- Esquire October issue featured active display on newsstand editions

Typical “Kool-Aid” Prediction
(2007-2014 Revenues by Market)

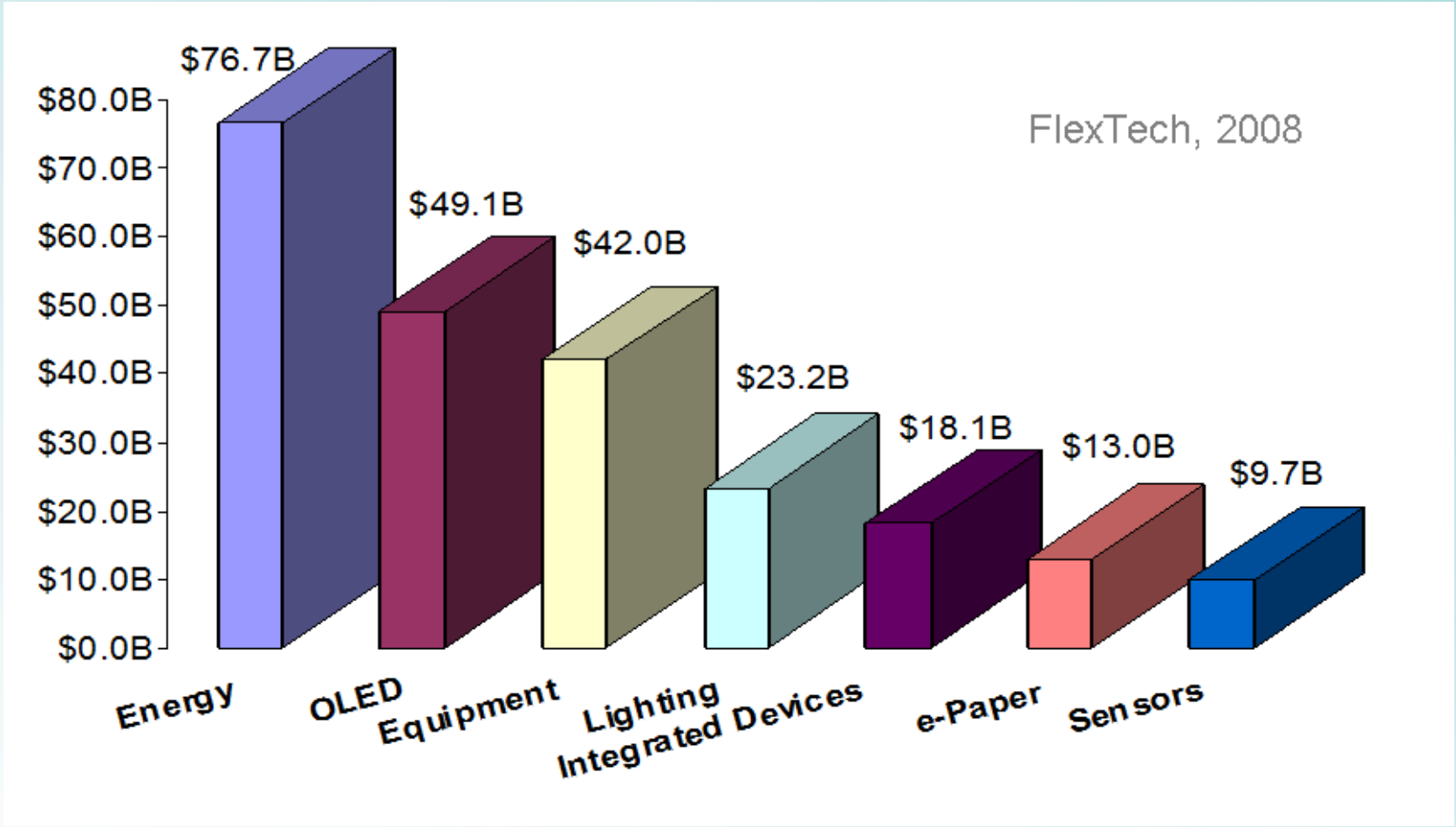


Copyright 2008 NanoMarkets LC

10 Year Prediction



Cumulative Revenues to 2017



Recent Venture Investments

Device Companies	Materials Companies
• Add-Vision	• Kovio
• Konarka	• Cambrios
• Nanoident*	• Coled Technologies*
• ORFID*	• Novaled**
• OrganicID *	• Nanogram
• Plastic Logic	• Plextronics
• E Ink	• Vitex Systems
• PolyIC*	• Sumation*
• Polymer Vision	• Nanosolar**

* size of investments have not been disclosed,

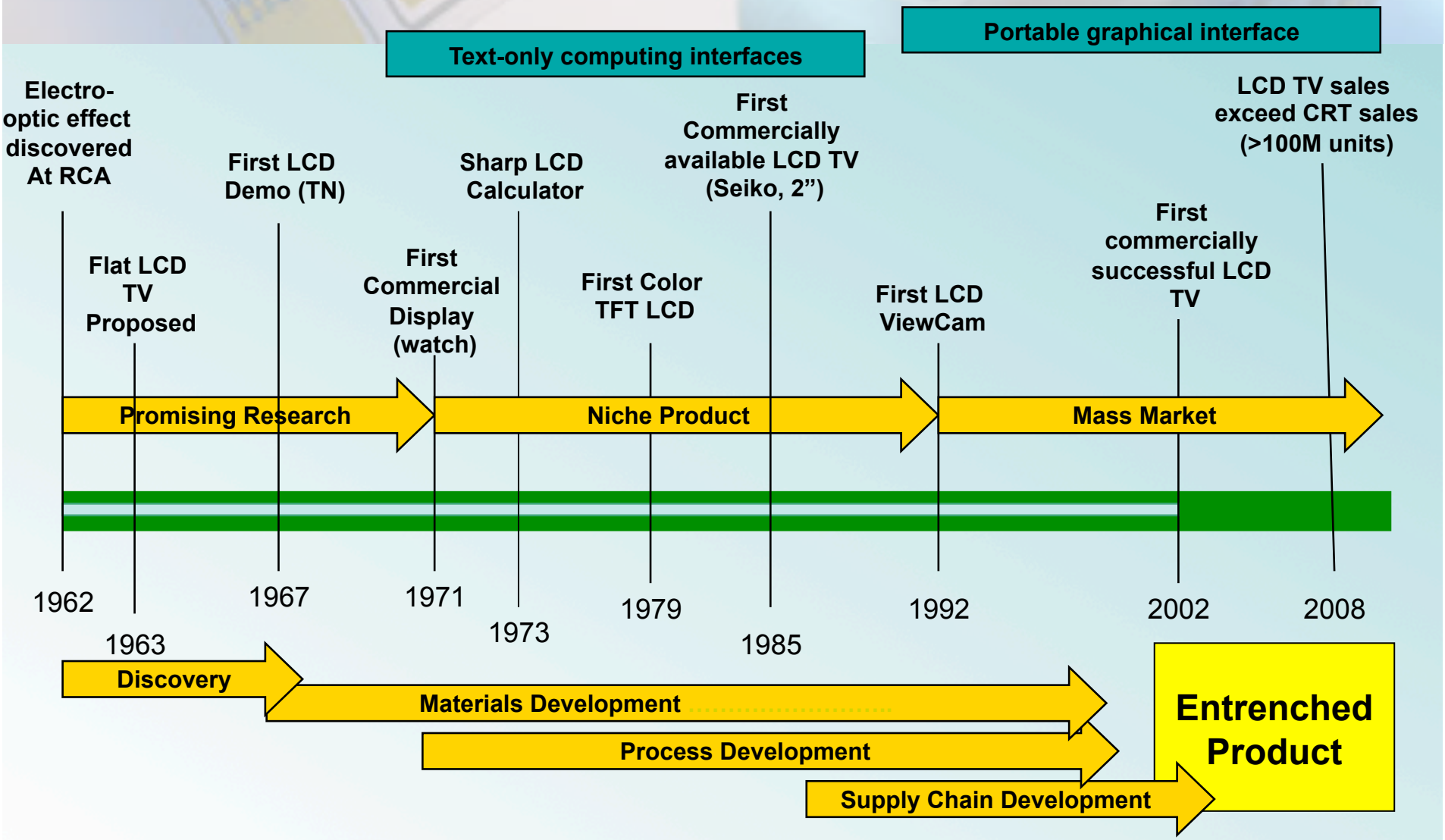
** could also be considered a device company

(cintelliq)

Notes on Venture Investments

- List is loaded - strong VC investment in production facilities (especially Europeans)
- Materials are perennial VC favorite
- More than 50 funded thin-film PV startups, at least 10 in excess of $100M
- Display and Mfg investments are out of favor

LCDs – A Case Study



Strong Opportunity Areas

Sensors

Novelty/Toy

Medical

E-paper

Authentication

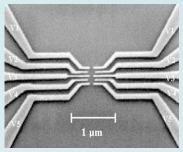
Wearable Electronics

Product Packaging

What Makes Them Attractive

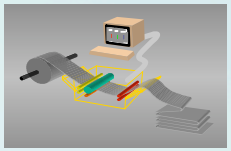
- Creates market rather than competing in existing market (no entrenched substitutes)
- Niche markets with mass market potential
- Electronics is a small part of product cost
- Solves a problem that can’t be easily addressed by existing technology
- Fits into an existing supply chain

Technology Development Opportunities



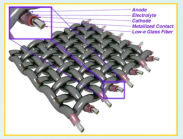
Materials

Barriers/Dielectrics
Conducting Inks
Flexible substrates



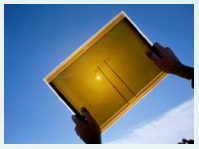
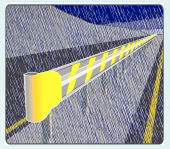
Processes

R2R Coating
Printing and Patterning
Registration/Inspection

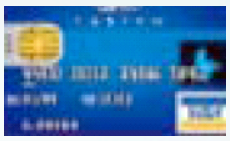
Devices/ Integration

Diodes
Sensors/Detectors
Thin-film transistors

Products

Smart Bandages & Clothing
Sensor Networks
Photovoltaics



Markets

Military – Information and Awareness
Medical – Monitoring and Implants
Energy – Storage and Harvest

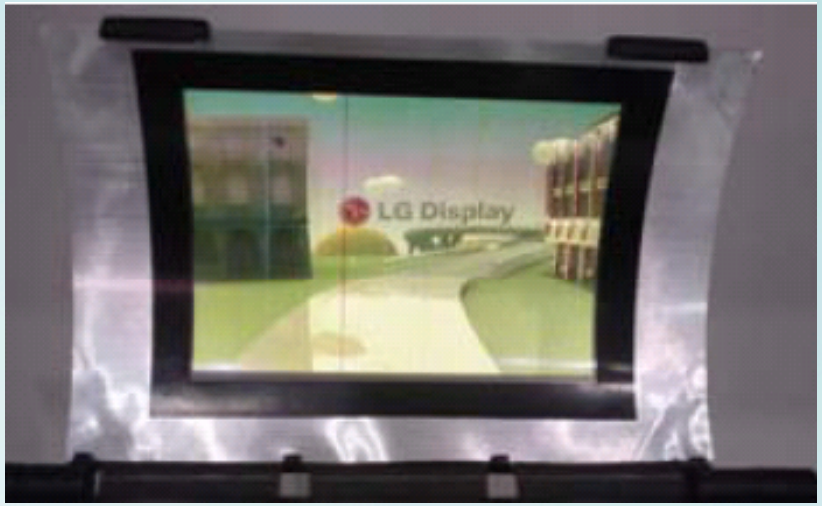
Some Less Attractive, but Large, Markets

General Lighting

iLED + waveguide ≡ OLED

Display Replacements

- Cell phone
- TV



What Makes Them Unattractive

- Competes with existing commodity product
- Large existing production infrastructure
- Doesn’t leverage existing production
- Solves a problem that can be addressed by existing technology

And By The Way

First Cost of Light for Various Sources in 2007

Light Source	**2007 First Cost of Light**
Incandescent Lamp (A19 60W)	$ 0.30 per klm
Fluorescent Lamp (F32T8)	$ 0.60 per klm
High-Intensity Discharge (250W MH)	$ 2.00 per klm
Compact Fluorescent Lamp (13W)	$ 3.50 per klm
ILED (1W Cool White)	$ 25.00 per klm
OLED (2008, Osram-Mauer)	$ 1,000,000.00 per klm

Picking a Technology Winner

A Few Items to Consider

- Beware of the Hype Curve
- Cost is not a meaningful technology driver
  - Except perhaps for disruptive technology
- The Market drives technology, not the other way around
  - Inherent physical limits on existing technology Aren't
  - Technology capabilities are predictable, even if the solutions are not
  - There is always a substitute for your solution

The Hype Curve

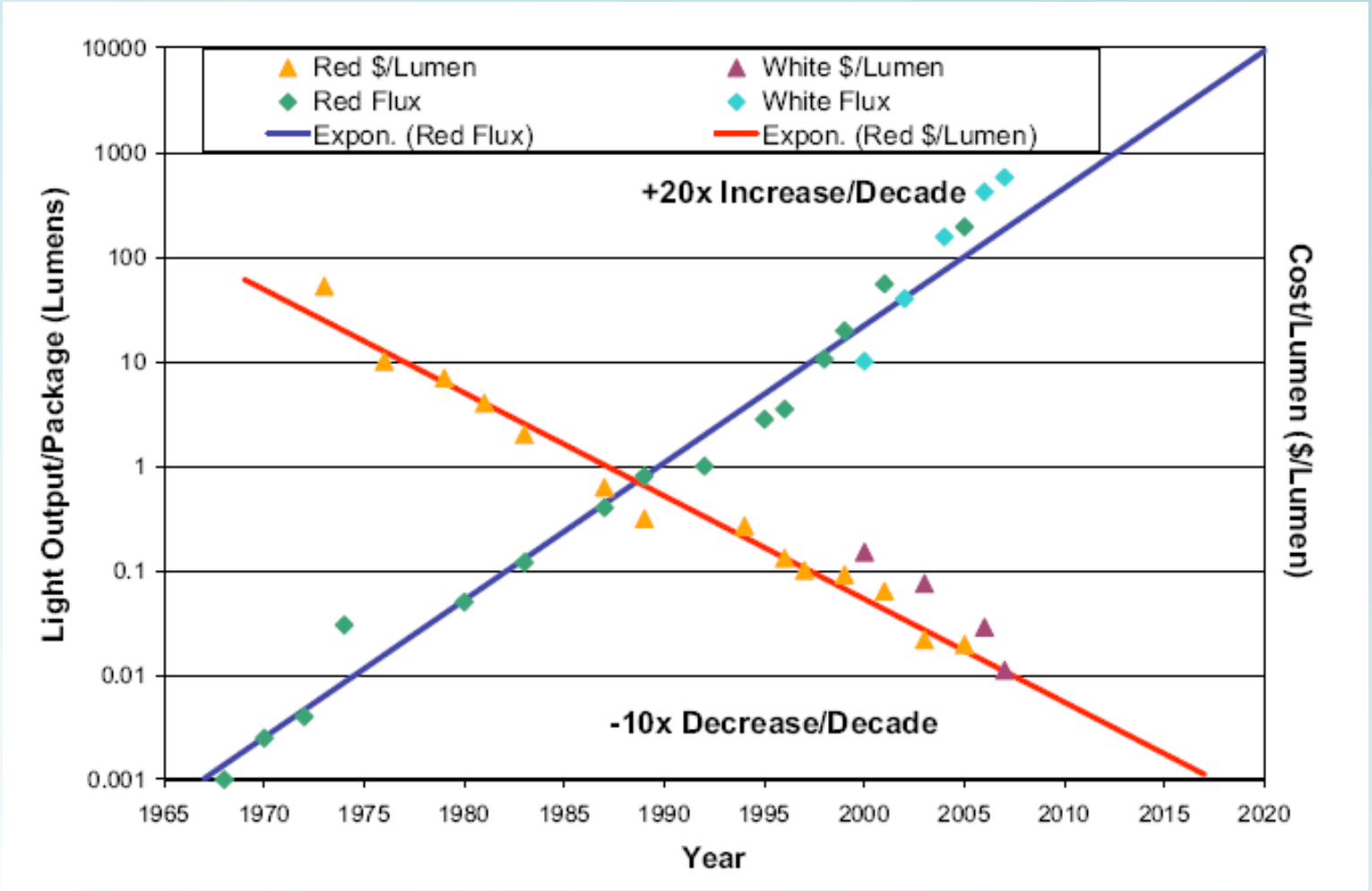
The Value of Cost

- Definition of “disruptive”: 10x more productive, or 10x less expensive than current technology
- Disruptive technologies:
  - Telephone
  - Telegraph
  - Radio
  - TV
  - Internet
  - Silicon microchip
- Printed Electronics is not a “disruptive” technology (although one could argue the case in medicine)

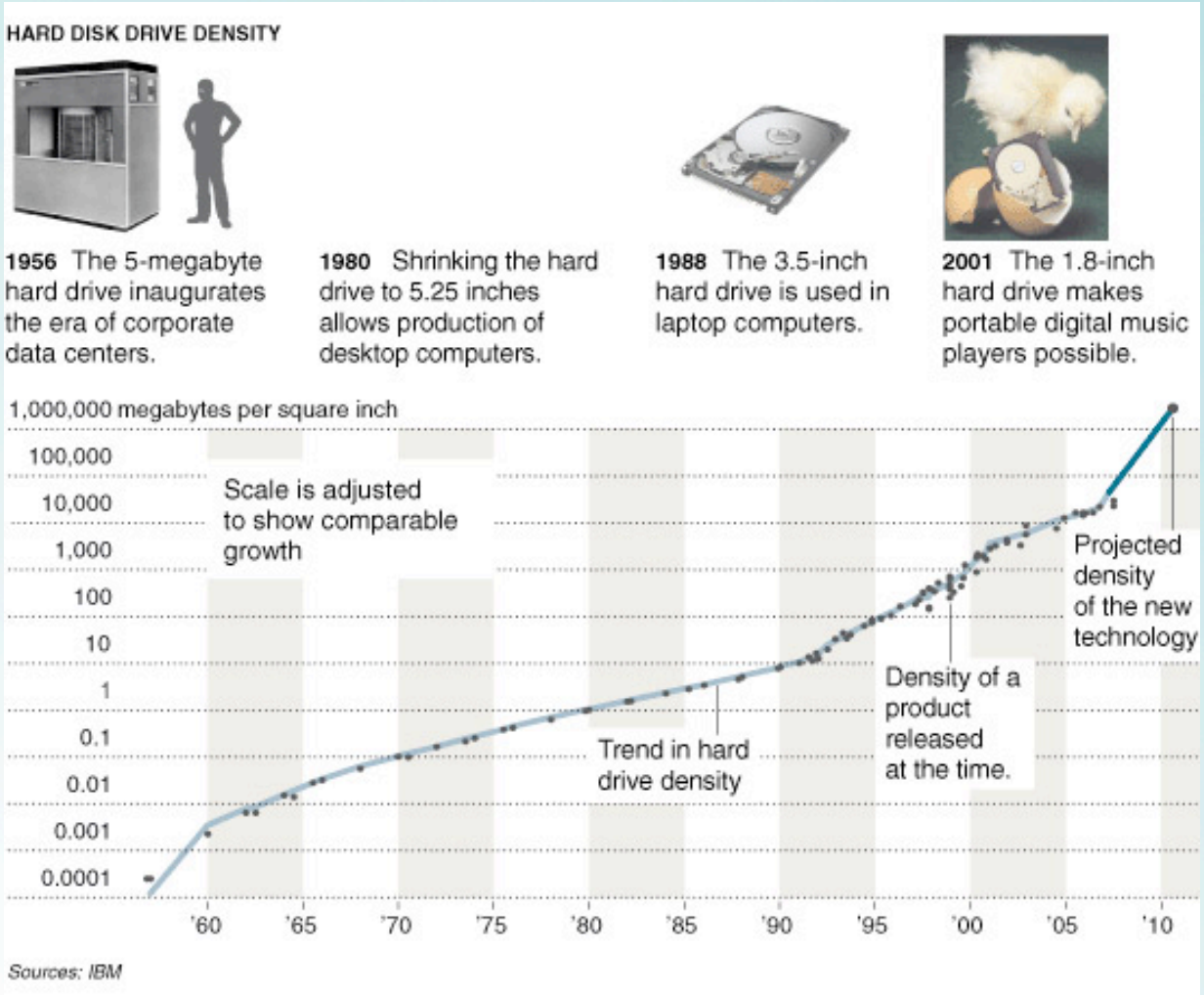
Predicting Technology Development

- Technology development is ruled by power laws
- Over long time periods change is smooth and predictable
- Remember that there is a lot of capital invested in entrenched technologies

Example LEDs – Haitz' Law



Example - Magnetic Storage

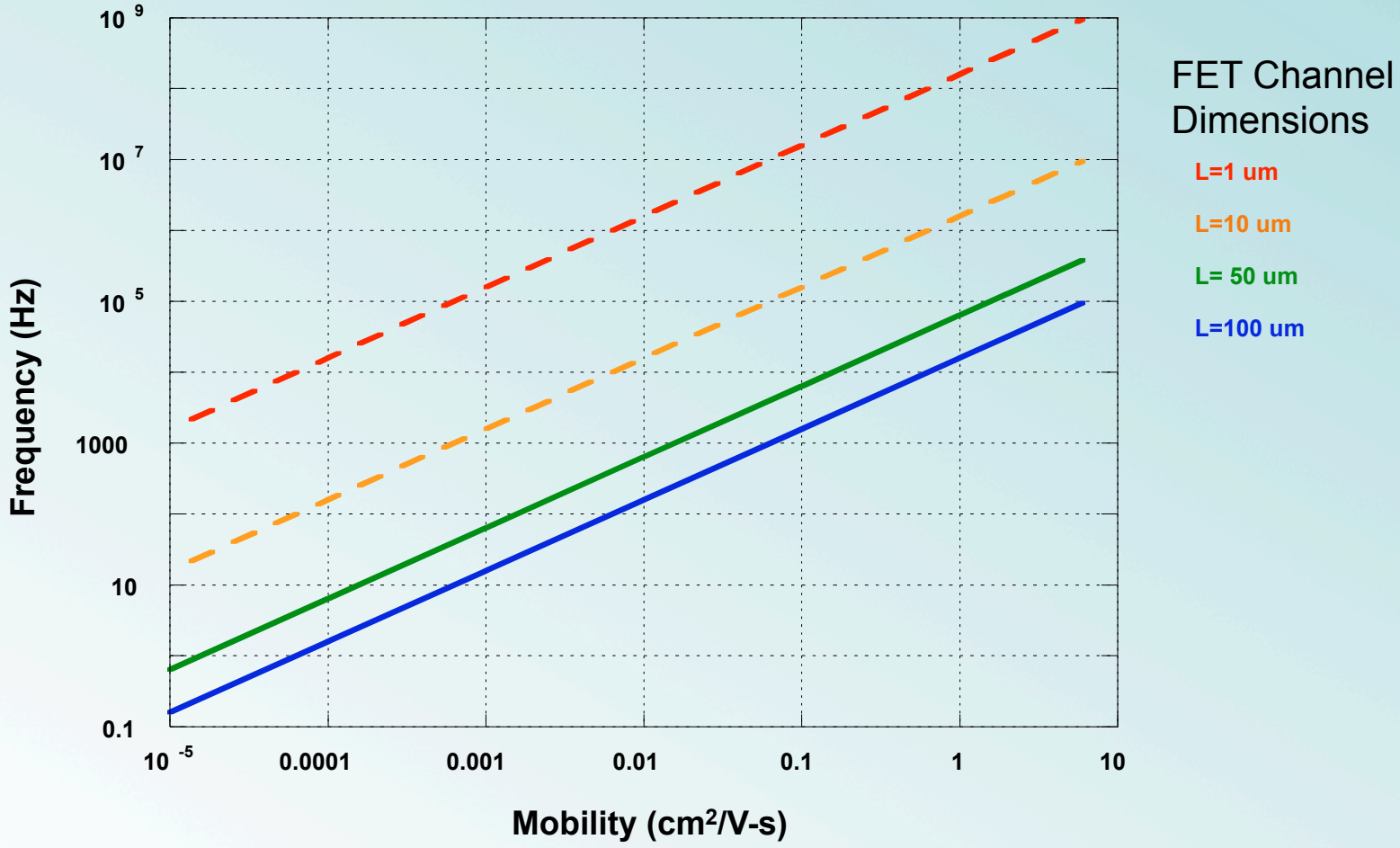


Magnetic disc technology reached "inherent physical limits" every 2-3 years starting in the mid 80's

Every time, the problem was quickly overcome

Circuit Performance

Semi Ink Mobility vs. Device Features



UniSolar Manufacturing Line

R2R Photovoltaic Deposition Line and Fabricated Roll

Off-the-shelf Volume Mfg

AKT SunFab

Thin-Film PV Enables Economies of Scale

AKT (AMAT) SunFab (example)

- a-Si PECVD, ~10k panel/month
- Gen 8.5 glass (5.7m^2 Modules)
- 55k m^2 of PV per month
- 40MWp annually (η=9%)
- Fixed cost/Wp = $1.75

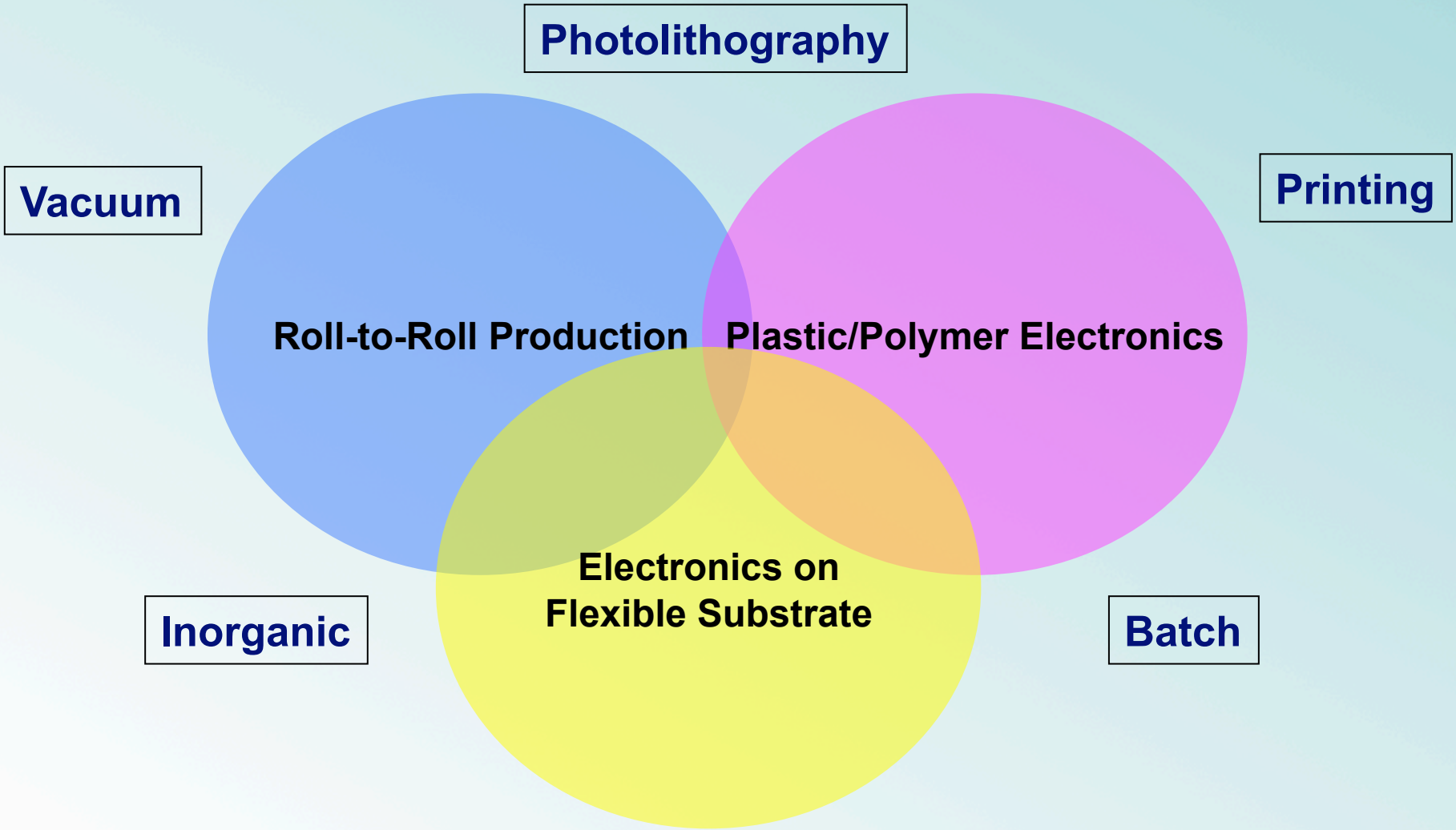
Monthly Roll-to-Roll equivalent:
55km of 1m web (13 x 600mm rolls)

First production panels in 2h08

Image borrowed from AKT

Upshot

(Whatever your concept of F/P E, it's likely wrong)



Funding Flexible/Printed Electronics Research

Directed Government Funding For Flex (2001-2013)

USA - $193M

- NIST-ATP, $12.2M
  - 2 Projects
- DARPA, $15M
  - Mesoscopic Integrated Conformal Electronics
  - Flexible Emissive Displays
- Army, $97.3M
  - FDC, Phase I
  - FDC, Phase II pending approval
- USDC, $69.3M
  - 40+ cost-shared projects

EU - $715M

- FP6, $186M
  - Advanced displays
  - Flexidis
  - Micro/nano sub-systems
  - OLLA
- FP7, $183M
  - Organic display systems
  - Organic Electronics
- BRD $265M
  - Initiative Organic PV
  - OLED Initiative
  - Smart labels
- UK $79M
  - CPI/CENAMPS

Investor Appetites

	Venture	Corporate	Gov't
Market size (TAM) (min)	~$2B	$200-500M	$0 (Desired)
Time to market (max)	5-7 years	1-3 years	15 years
Customer Base	Diverse	Broader is better	Strategic
IRR	>40%	≥COC (typically 13-18%)	5-7%
Market Dynamics	Emergent + Strong Growth	Predictable Cash Flows	Need Driven

Summary

- Flexible/Printed electronics are in the marketplace (not just hype anymore)
- PV and displays drive near-term growth
  - Economy of scale catch-22
  - Enable new products in each category
- Hybrid production technologies will continue to open high margin markets
- Near-term volatility in emerging products

Contact Information

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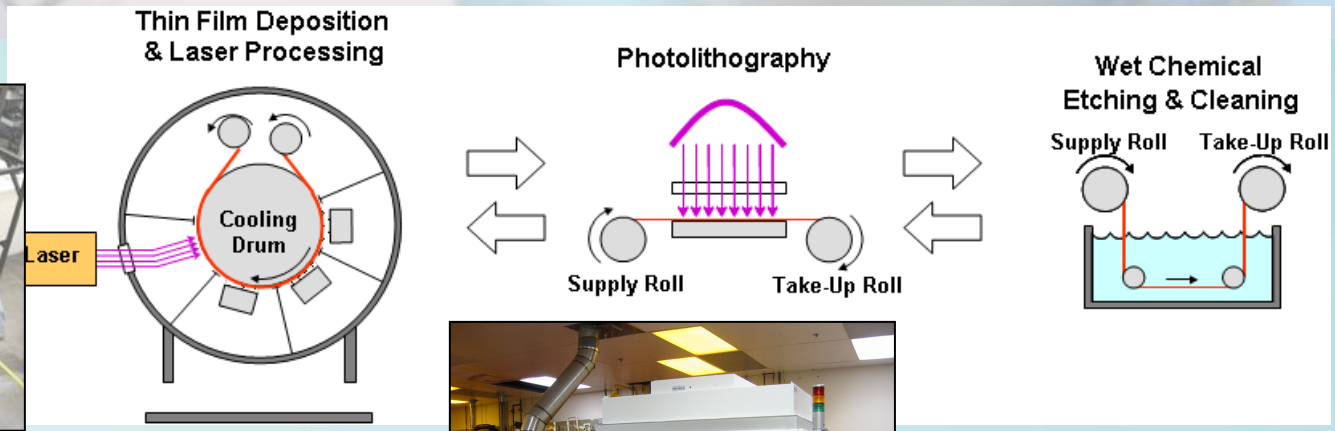
From Hybrid to Roll-to-Roll




Northfield R2R Handlers


Azores Photolithography

R2R can lead to reductions in cost.
R2R can enable new applications:

- Inexpensive displays
- Large area displays
- Low cost RFID
- Remote sensors for military and commercial
- “Smart” fabrics
- Large area lighting

CAMM
The Center for Advanced Microelectronics Manufacturing